Mercury-Cadmium-Telluride Focal Plane Array Performance Under Non-Standard Operating Conditions for Warm Alignment of Imaging Spectroscopy Systems

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Abstract- This paper highlights a new technique that allows the Teledyne Scientific & Imaging LLC TCM6604A Mercury-Cadmium-Telluride (MCT) Focal Plane Array (FPA) to operate at room temperature.

The Teledyne MCT FPA has been a standard in Imaging Spectroscopy since its creation in the 1980's. This FPA has been used in applications ranging from space instruments such as CRISM, M^3 and ARTEMIS to airborne instruments such as MaRS and the Next Generation AVIRIS Instruments[1]. Precise focal plane alignment is always a challenge for such instruments. The current FPA alignment process results in multiple cold cycles requiring week-long durations, thereby increasing the risk and cost of a project. These alignment cycles are necessary because optimal alignment is approached incrementally and can only be measured with the FPA and Optics at standard operating conditions, requiring a cold instrument. Instruments using this FPA are normally cooled to temperatures below 150K for the MCT FPA to properly function. When the FPA is run at higher temperatures the dark current increases saturating the output. This paper covers the prospect of warm MCT FPA operation from a theoretical and experimental perspective. We discuss the empirical models and physical laws that govern MCT material properties and predict the optimal settings that will result in the best MCT FPA performance at 300K. Theoretical results are then calculated for the proposed settings. We finally present the images and data obtained using the actual system with the warm MCT FPA settings. The paper concludes by emphasizing the strong positive correlation between the measured values and the theoretical results.

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1. Introduction

Focal plane alignment remains one of the most critical steps in the assembly of Imaging Spectroscopy Systems. Great time and expense are dedicated to precisely positioning the focal plane within a fraction of a millimeter in the optical system. Proper focal plane placement can only be verified with an operational focal plane at standard operating temperatures, below 150K. This often requires multiple cold cycles to complete the alignment process. Acceleration of the alignment process is greatly desired in the imaging spectroscopy community. The difficult and cumbersome methods used in the past for focal plane alignment often caused schedule slips and budgeting issues at the end of an instrument build when reserves are low, zero, or negative hence adding pressure to an already difficult task.

In a standard alignment scenario the first few cold cycles allow the FPA to be roughly placed in the optimal position. The later cold cycles fine tune the positioning for near perfect alignment. These later cycles take into account the deformation of the opto-mechanical mounts at low temperatures. The ability to run the MCT FPA at room temperature allows the first few cold cycles to be eliminated. The final cold cycle is still necessary for fine tuning because of the mount deformation caused by the cryogenic temperatures. The ability to run the FPA at room temperature is especially beneficial during these final crucial steps to assure the FPA is adjusted in the right direction and by the correct amount.

Initially this problem was approached in theory using simple assumptions coupled with empirical models of MCT FPA behavior characteristics. These models provided a starting point for the testing that followed. After multiple trials the optimal settings were determined.

2. Theoretical Foundations

During normal MCT focal plane operation at cryogenic temperatures the dark current contribution to the signal is quite small filling only a tiny fraction of the well. As the FPA operating temperature increases the dark current contribution soon becomes the primary factor, overwhelming any optical signal and saturating the sensor. This effect quickly becomes apparent when running a MCT FPA at factory settings near room temperature, the outputs are completely saturated.

External Radiative Limit

There are many factors that play into the dark current observed in detectors. Even ideal detectors will have a dark current contribution defined by the External Radiative limit. The External Radiative limit sets the absolute minimum possible dark current an ideal detector would have based on the Blackbody radiation it emits. With a quick back of the envelope calculation we can determine if it's even physically possible to run an MCT detector at 300K. Assuming the detector and surroundings will be held at 300K we can approximate the dark current contribution caused by black body radiation from the environment using Planck's law of black-body radiation, Equation 1, along with the cutoff wavelength of the MCT and the pixel size.

$$I(v,T)dv = \left(\frac{2hv^3}{c^2}\right)\frac{1}{e^{\frac{hv}{kT}}-1}dv \qquad (1)$$

Band Gap Temperature Dependence

Unfortunately, the cutoff wavelength of the MCT material is not a constant, it is temperature dependent. At normal operating temperatures (140K) the detector has a cutoff wavelength of 2.55µm. Using the results presented by G.K. Hansen et al[2], the Bandgap Energy at 300K can be approximated using Equation 2 and then converted to the cutoff wavelength using Equation 3. The NGIS MCT FPA has a cadmium fraction *x* of around 0.45. Figure 1 presents the cutoff wavelength as a function of temperature for the NGIS Detector material. From this data we determine that the cutoff wavelength at 300K is around 2.51µm.

$$E_g = -0.302 + 1.93x - 0.81x^2 + 0.832\,x^3 + 5.35 * 10^{-4}T(1-2x) \qquad (2)$$

$$E_g = \frac{h*c}{\lambda_{co}} \qquad (3)$$

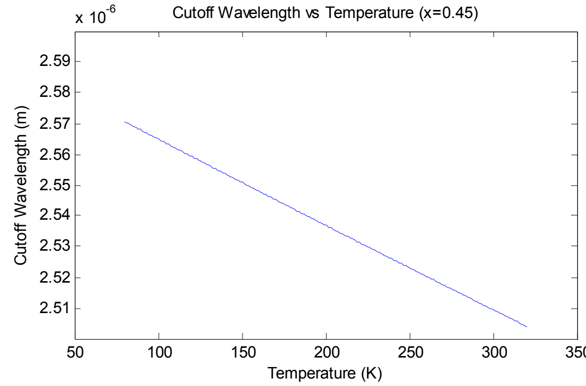

Figure 1: MCT Cutoff Wavelength vs Temperature

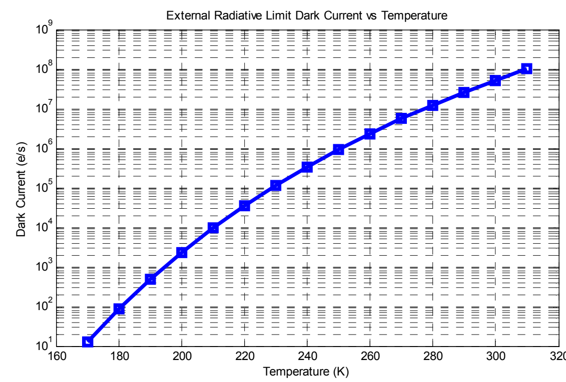

Figure 2: Showing the approximate Dark current (e/s) from the external radiation temperature.

"Rule 07" Empirical Model

Unlike ideal detectors, real detectors have additional dark current contributions from imperfections. The external radiative limit of performance is usually two or three orders of magnitude better then the best MCT devices available. Defect generation centers and Auger recombination mechanisms limit the overall performance of real detectors. Equation 4 is the "Rule 07" empirical model presented by W.E. Tennant[3] in the Journal of Electronic Materials. When applied correctly, this model provides the attainable dark current performance level that can be expected from MCT devices.

$$J = J_o\, e^{C\left(\frac{1.24}{\lambda_e}\right)\left(\frac{q}{kT}\right)} \qquad (4)$$

$$\lambda_e = \lambda_{cut-off}$$
$$for\ \lambda_{cut-off} \geq \lambda_{threshold}$$

$$\lambda_e = \frac{\lambda_{cut-off}}{\left[1 - \left(\frac{\lambda_{scale}}{\lambda_{cut-off}} - \frac{\lambda_{scale}}{\lambda_{threshold}}\right)^{Pwr}\right]}$$
$$for\ \lambda_{cut-off} < \lambda_{threshold}$$

Where:

$C = -1.162972237$
$Pwr = 0.544071282$
$J_o = 8367.000019$
$\lambda_{cutoff} = 2.51\mu m$
$\lambda_{scale} = 0.200847413$
$\lambda_{threshold} = 4.635136423$

Figure 3 shows the "Rule 07" empirical model Dark Current results as well as the approximate external radiation Dark Current limit. As expected the "Rule 07" model does predict a larger detector dark current then the theoretical limit. However, we can already see that the dark current rate is about 1000 times more than the signal rate for a 293K blackbody when the detector is at 300K. This suggests that when warm the detector will have a lower sensitivity then when the detector is cooled.

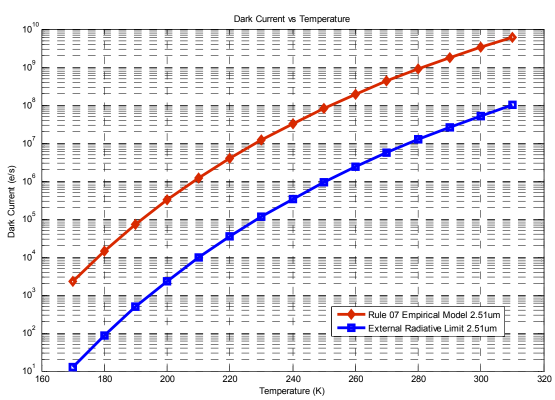

Figure 3: Showing the approximate Dark current (e/s) from the "Rule 07" Model and the External Radiation Limit.

Atmospheric Dark Current Leakage Contribution

Other important leakage mechanisms play into the dark current estimate. First, MCT sensors are traditionally designed and operated at very low temperatures requiring the use of a vacuum chamber. While in operation the detectors are held under vacuum to avoid condensation and the deposition of airborne particulates on the FPA surface. When operating the detector at room temperature (300K) the vacuum chamber does not have to be used. Running the FPA at atmospheric conditions introduces another source of leakage current. Based on observation there is about 1pA ($6.24151*10^6$ e/s) of electrical leakage due to the pressure differences. This effect will not be accounted for in the "Rule 07" model and needs to be added separately.

Using the data from the "Rule 07" Model along with the integration time of the detector the number of dark current electrons collected can be calculated. The Teledyne 6604a detector clocks at 4Mhz outputting a maximum of 100 frames per second. The shortest integration time possible is 2 lines, $(1/100)*(2/480)=4.166*10^{-5}$ seconds. With the detector at 300K running at the shortest integration time the "Rule 07" Model predicts that $1.4018*10^5$ electrons will be collected. The amount of electrons collected due to the atmospheric water vapor is approximately ($6.24151*10^6$ e/s)*($4.166*10^{-5}$ s) = 260 electrons. Summing these values provides the total number of electrons collected over the $4.166*10^{-5}$ second integration time.

The TCM 6604a has a Well Depth of $8.22*10^5$ electrons. Therefore, a warm FPA (300K) running at the shortest integration time possible will have a dark current contribution of approximately 17% of the full well capacity. We conclude that it should be possible to get a useable photon signal output from these devices at room temperature.

3. Optimizing the MCT Focal Plane at 300K

The dark current calculations performed in the previous section model the expected dark current of an MCT device at factory settings. Modifications to the factory settings can change the dark current measured. Optimizing the factory setting for MCT detector operation at 300K involves adjustments of both the internal and external biasing options.

Internal Biasing Options

Many manufacturers use a given Readout Integrated Circuit (ROIC) for many types of detectors ranging from MCT devices cooled to LN2 temperatures to Silicon devices designed to function at higher temperatures. Therefore, the ROIC is design to operate efficiently over a wide range of temperatures. This functionality can be used to our advantage when running an MCT device warm. Normally a set of temperature dependent biases are generated on the ROIC and can be adjusted via an external "Mode" pin. Choosing the setting that allows the ROIC to run optimally at 300K will assure no artifacts appear in the output caused by improper circuit biasing.

The Effect of Reverse Bias on Dark Current

Many MCT devices require a series of external DC bias voltages to operate. These voltages typically provide power for the basic electrical functions (i.e output amplifiers, column buffers, digital electronics), they also set the reverse bias voltage of the detection diode on the unit cell. Since these DC bias are externally supplied, modifications can easily be made. Examination of a MCT diode current voltage characteristics (Figure 4) reveals that in the reverse bias region the current flowing through the diode is a function of the reverse bias voltage.

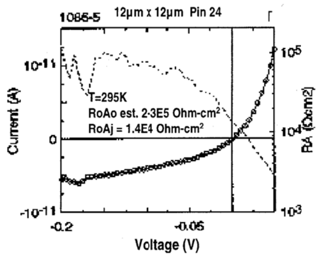

Figure 4: The Current Voltage characteristics of an MCT 12 µm square diode at 295K; from W.E. Tennant[4]

By applying this model to the detector's unit cell the dark current contribution can be reduced considerably by reducing the reverse bias voltage across the detection diode. This is a fine tuning process, ideally zero reverse current flow is desirable, however, that only occurs at a reverse bias voltage of zero. Unfortunately, zero reverse voltage impedes the diodes ability to detect light, therefore a finite reverse voltage is necessary. Through experimentation a reverse bias voltage setting can be chosen to reduce the dark current thereby enhancing the sensitivity of the warm detector.

4. RESULTS

Imaging Results

By applying the modifications summarized in the last section, the MCT detector can properly image at 300K. The sensitivity of the device is rather low, as expected, but simple imaging can easily be achieved. The results shown below were obtained by imaging a simple scene onto the Focal Plane using a 50mm f1.8 Computar c-mount lens. The scene, as shown in Figure 5, is a wrist watch on a black mat. Because of the low sensitivity of the warm detector it is necessary to illuminate the scene with 150W light. Getting the correct focus was difficult, the images still appear a little out of focus.

Figure 5: Image of the scene taken before the testing using digital camera (Before Illumination by 150W lights)

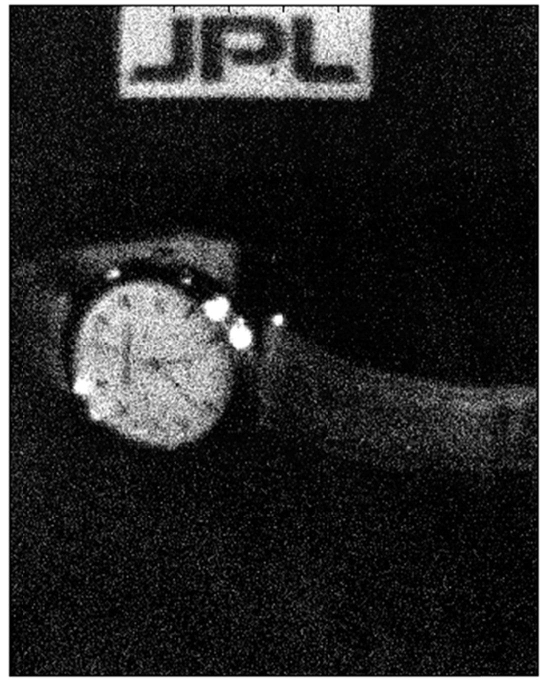

Figure 6: Image taken with the MCT Focal Plane at 300K

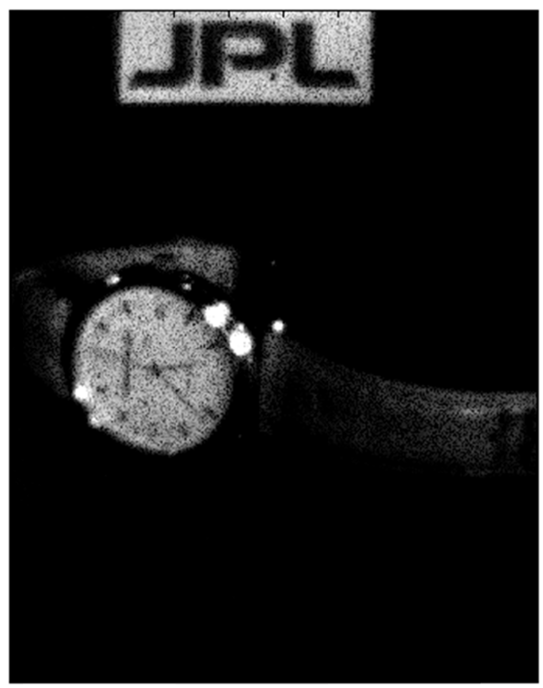

Figure 7: Dark Subtracted Image taken with the MCT Focal Plane at 300K,

It is apparent from Figure 6 that the dark level on the focal plane while running warm is not very uniform. On average the dark level is approximately 978DN but the standard deviation across the focal plane is 116DN. This makes dark subtraction an essential component of the imaging process.

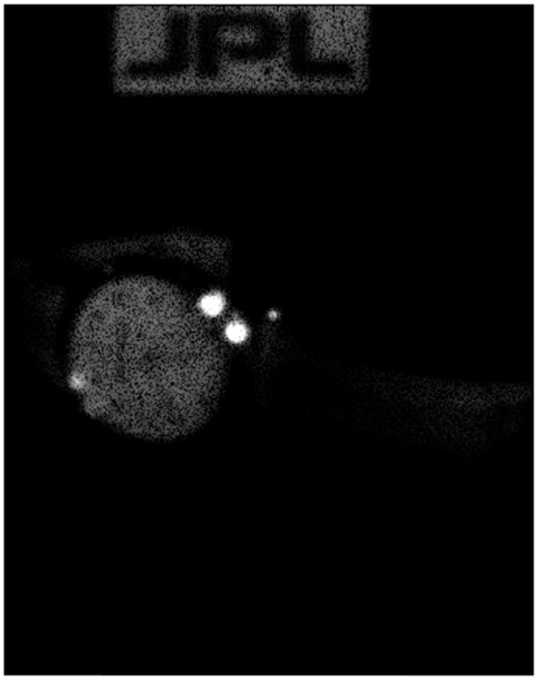

Figure 8: Dark Subtracted Image taken in the near infrared with the MCT Focal Plane at 300K using a 1mm thick silicon wafer filter ($\lambda_{cutoff} = 1\mu m$)

Figure 8 conclusively verifies that the MCT material is active and is capable of detecting light in the infrared. To further test the infrared capabilities of the detectors a series of filters were used to scan through the wavelengths. Figure 9 provides the transmittance spectrum of the final band pass filter used to detect light with the sensor. This filter passes light from 2μm to 2.25μm.

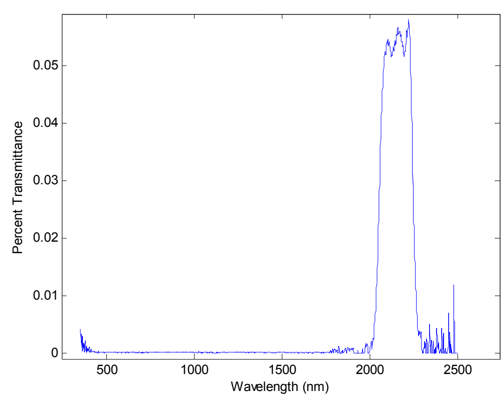

Figure 9: Transmittance Spectrum of the final filter

The output of next available filter (which has a cutoff of 2.55μm) was not detectable by the focal plane, implying that the cutoff of the FPA lies somewhere between 2μm and 2.55μm. This is consistent with theory which suggested a cutoff of 2.51μm.

Dark Current

Using seven different integration times, with a blinded 300K MCT detector the dark current can be determined. Figure 10 shows the change in DN for the seven integration times.

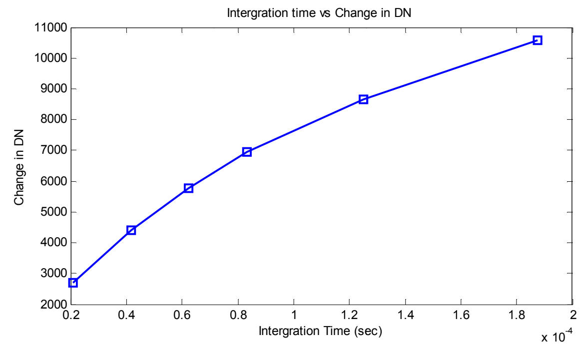

Figure 10: Dark 300K MCT Focal Plane Integration time vs. Change in DN

Figure 11 shows the results from a quick and simple test, using only two light levels, to determine the 300K Photon Transfer Gain. Using the Astronomers Method as described by Donald F. Figer[5], the Photon Transfer Gain at 300K is calculated to be 31 electrons per DN. This is a reasonable assessment of the gain considering we expect it to be similar to the Transfer Gain at 130K which was 45 electrons per DN.

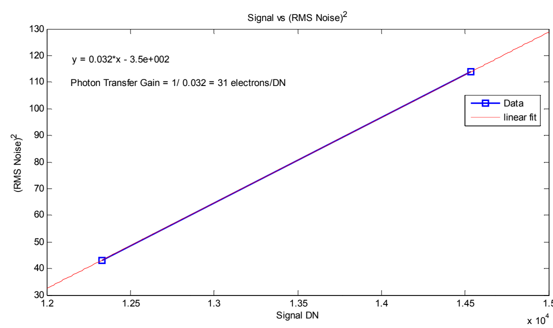

Figure 11: Photon Transfer Gain Estimation

The Dark Current is then approximated to be $2.77*10^9$ electrons per second. Considering Figure 10 has a small non-linearity the dark current approximation given here is the average of the seven data points. This dark current fits well with the theoretical "Rule 07" value ($3.3644*10^9$ electrons per second) calculated in the last section. The difference between the theoretical value and the actual value is most likely due to the reverse bias modifications.

5. CONCLUSION

The assembly of Imaging Spectroscopy Systems has been hindered for years by the FPA alignment process. Improvements in the Focal Plane alignment process are greatly desired to eliminate schedule slips and cost overruns. The application of warm MCT focal plane operations will drastically reduce the countless cold cycles necessary for precise focal plane positioning.

Utilizing empirical models and basic laws the plausibility of warm MCT operation was determined. Further investigation into the detector design revealed opportunities to optimized the MCT detector for use at 300K. Appling these modifications, warm MCT focal plane operation was achieved with minimal modifications to the drive electronics. Simple imaging with the detector was accomplished in both the visible and near infrared. Verification of the theoretical MCT cutoff wavelength at 300K was obtained using band pass filters. Finally, The Photon Transfer Gain was approximated and the dark current of the warm detector was measured and compared to empirical model prediction.

Further investigation into the MCT physics and the ROIC design may yield additional insight allowing the detector to be further optimized for operation at 300K. With the use of dark frame subtraction scientific imaging may be possible.

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BIOGRAPHY

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